WEB TENSION REGULATORS – CONTROL HEURISTICS

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ABSTRACT

Classical Control Theory using closed-loop controllers has been applied to drives for web handling beginning in the 1940's. Back then the mathematics was ahead of the tools for analysis as well as the modeling and the drive control equipment available. Nevertheless, using frequency domain analysis such as Bode Plots, and well thought out heuristics, strategies were developed for web tension control that were successful in developing the web handling drive systems at that time and continuing to the present. The control strategy heuristics developed in the 1940's are still in widespread use today although with newer equipment. It may be that these heuristics are so ingrained, that first principles are being forgotten or ignored.

Newer drives, controllers and tension measurement have resulted in drive systems with better specifications, but improvements in tension control may not be evident. Modern Control Theory state-space controllers are now available, but must be implemented in ways that do not ignore the web tension control strategies developed over the past 60 years. At a minimum, we expect new controllers will provide improved performance over classical controllers. This paper documents the classical heuristics developed for and used in drive systems for web handling machinery. It will discuss some practical concerns of implementing modern tension control algorithms in the web handling industry. These concerns include engineering and commissioning of the web tension control.

NOMENCLATURE

Transfer function **–** this is the ratio of the output over the input of a function in the Laplace domain.

Bode Plots **–** logarithmic graphical portrayal of frequency response named for H.W. Bode

***Heuristics* –** experience based techniques for solving problems

***Characteristic equation* –** the denominator of a transfer function whose roots (poles) determine its character

***Open Loop Transfer Function* –** a transfer function without closed loop regulator response and complexity

***Regulator Response (Bandwidth)* –** a measure of regulator performance

Convolution integral- describes how 2 functions overlap over all time as one is shifted past the other. This has application in cascading regulator blocks or transfer functions.

INTRODUCTION

Today drives for web handling lines are designed by control engineers with a bachelor's degree or by experienced technologists. Reliance on earlier designs and budgets, time constraints and inadequate modeling skills result in drive systems being shipped to site with very little in the way of control design. We find that motor power and RPM are calculated and delivered correctly. We find that the drive system includes excellent hardware and software tools from many vendors. Load cells are sized appropriately, but the position and wrap angle may not be optimum. Very little design goes into inertia compensation. Target regulator response or bandwidths may not even be specified. We can almost predict that a torsional or half critical resonance will be a problem at normal operating speeds of the line. Almost no thought is given to friction and windage. Winders and unwinds often take weeks to commission.

In the past, drive system engineering was done using the tools available at the time. That was typically some log-log graph paper, a straight edge and slide rule. The physics textbook was not far away. As technology improved, closed loop regulators were used. Frequency methods such as Bode plots were used to design the drive regulators. Transistors and operational amplifiers replaced carbon piles and vacuum tubes. Motor-Generator sets were replaced with static drives. Digital drives replaced analog drives. Ac drives replaced dc drives. The technology was adapted as appropriate because engineers knew exactly where last year's design was weak and how the new technology could improve performance.

This engineering came at a high price and was applied in industries that could afford the cost, namely metal rolling and paper production. Strategies were adopted to regulate torque, then speed, then tension. Open loop or feed forward models were applied before closed loop regulators were available and continue to today.

Models were analyzed, first with analog computers and later with the company digital computer.

100mm thick instruction books were provided for commissioning and tuning the drives. Drives were commissioned by trained technologists or engineers with a lot of experience. A good technician carried appropriate hand tools, a multimeter, chart recorder and calculator.

ASSUMPTIONS

The engineers who developed drives for web handling were incredibly clever. They were limited by the math and computation available in the day. A number of assumptions and simplifications were made in the models they used for analysis of web handling.

Classical control theory applies to linear time-invariant systems only. Control engineers knew that the systems were non-linear. In fact every new generation of hardware introduced more non-linearities culminating in drives with Thyristors or Pulse Width Modulation. Linear techniques were used to mask the non-linear elements.

Analysis was done for single drives or single web spans.

ANALYSIS

Control theory for drive controls from 1930 to 1990 and perhaps 2000 was based on frequency domain analysis (Laplace domain). Before computers were widely available (1970's), graphical charting methods were developed to assist in analyzing the control system (Bode Plots named for Hendrik Wade Bode). The industry was well established by the 1960's and 1970's, using techniques suitable for straight edges and slide rules and without computers. When computers were used, they were as often as not analog, rather than digital computers. Analog computers could be made of the same components and circuit cards as the drives they were simulating.

Web handling regulators were developed for profitable industries of the era. Those were metal rolling and to a far lesser extent paper. The experience gained in those industries was applied to plastics and laminates later. It is fair to say that an attempt was made to model all parts of a metal rolling line with tools available in the 1960's and 1970's. Metal rolling at the time was a batch process. For metal rolling, web handling factors such as tension determine metallurgical properties of the web. That is tension, pressure and temperature affects the crystal formation in the alloys. Additionally, visible tension related elongation effects were controlled as billets were roughed into webs (strips). As the head of a billet hit each roller stand a disturbance to roller speed and of course tension was introduced. A fast responding regulator reduced the amount of waste associated with the head of each billet. Of course all the normal defects common to web handling were addressed.

The economics of the paper industry were an order of magnitude smaller than for metal rolling at that time. Very little modeling or simulation of drive systems was done for the paper industry. Of course, the same engineers working with metal rolling would occasionally work on a paper job. We would all eat lunch together. We could also coax the landlord of the analog computer to run a simulation for a paper winder. The metal rolling profit center had the resources, achieved regulators 5 times faster than those in paper mills and its engineers received the big salaries.

The occasional plastic embossing line was considered a "filler job" and very little modeling was done.

BODE AND LAPLACE METHODS

Stated without proof is that multiplication in the frequency domain represents convolution in the time domain in which we live. Electrical and control engineers have found brain cell destroying activities which are much more pleasurable than solving convolution integrals. We therefore calculate in the frequency domain.

Also stated without proof is that convolution applies to the cascading of control functions including filters, regulators and the transfer functions used in control.

These transfer functions of frequency can be determined by several methods of measurement. The historical method is to apply a sinusoidal input of constant magnitude to the input of a system and measure the absolute value of the output as well as the phase shift of the output. The results can be plotted on a Bode Plot. The second method is to perform a Fast Fourier Transform (FFT) of the system. I had a fun learning experience in a paper mill once using a structural dynamic analyzer to apply a frequency varying sinusoidal input to the torque reference for a 300 KW motor. Everyone in the building agreed that torque can be expressed as a function of vibration.

The transfer function can also be determined by manipulation of the Ordinary Differential Equation (ODE) of the system (modeling) and then performing the Laplace Transform mathematically or with conversion tables.

Frequency Transforms simplify differentiation and convolution into multiplication and integration into division.

There are two frequency domain transformations used to express control functions. These are the Fourier transform and the Laplace transform. The transforms have strong similarities, but are not identical. The frequency parameters are jω (Bode) and s (Laplace) with units of radians/second. I will use sl (units of complex radians/second) for the Laplace argument and s for seconds.

Fourier Transform

$$F(j\cdot\omega) = \int_{-\infty}^{\infty} f(t)\cdot e^{-j\cdot\omega\cdot t}\, t \qquad \{1\}$$

Laplace Transform

$$F(s) = \int_{0}^{\infty} f(t)\cdot e^{-sl\cdot t}\, t \qquad \{2\}$$

$j\cdot\omega$ – frequency in radians/second times $j = \sqrt{-1}$ is used in Bode plots. This typically is used for steady state response calculations.

sl – Laplace frequency in radians/second times a complex number. This is used for transient and steady state equations.

The Bode plot was developed using the open loop transfer function to study a closed loop regulator. The open loop transfer function GH(frequency) is easy to measure using tools common to electronics industry. Adjusting the frequency until the open loop gain is unity is a measurement method of solving the poles of the characteristic equation.

Laplace domain methods such as Nyquist or Root Locus plots use the closed loop transfer function. Modern control theory also uses the closed loop transfer functions. A closed loop transfer function can be shown in a block diagram and simplified using algebra or block transformations.

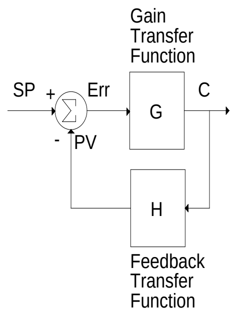


Figure 1 – Closed Loop Transfer Function

$$\frac{C(sl)}{SP(sl)} = \frac{G(sl)}{1 + G(sl)\cdot H(sl)} = \frac{\sum_m \left(b_m \cdot sl^m\right)}{\sum_n \left(a_n \cdot sl^n\right)} \qquad \{3\}$$

$\sum_n \left(a_n \cdot sl^n\right)$ is the characteristic equation and is used for closed loop regulator analysis.

The modern state-space representation is in the form of these matrix equations.

$$y = C\cdot x(s) + D\cdot u(s) \qquad \{4\}$$

$G(sl)\cdot H(sl)$ is the open loop transfer function.

Classical control theory established that almost everything interesting regarding regulators happens when the characteristic equation equals zero. The solutions (roots) of the characteristic equation are ***poles*** of the system. Modern (State-Space) control theory uses the eigenvalues of the state matrix A.

1-GH is not identical to the characteristic equation. In particular, the numerator may introduce additional poles. Bode, in an effort to keep the math simple, stopped the algebra at the earliest stage of the closed loop equation. The closed loop transfer function poles are solutions of |GH| = 1. GH is the open loop transfer function and may be determined by several practical methods. Components of this transfer function can be measured independently and multiplied together in the frequency domain.

Below is a polar plot in the complex plane which represents the transfer function of a simple Butterworth low pass filter with frequency as the parameter. The poles of the characteristic equation are where the line crosses the unit circle.

Butterworth Filter

$$T(sl) = \frac{G}{(j \cdot sl)^2 + \sqrt{2} \cdot j sl + 1} \qquad \{5\}$$

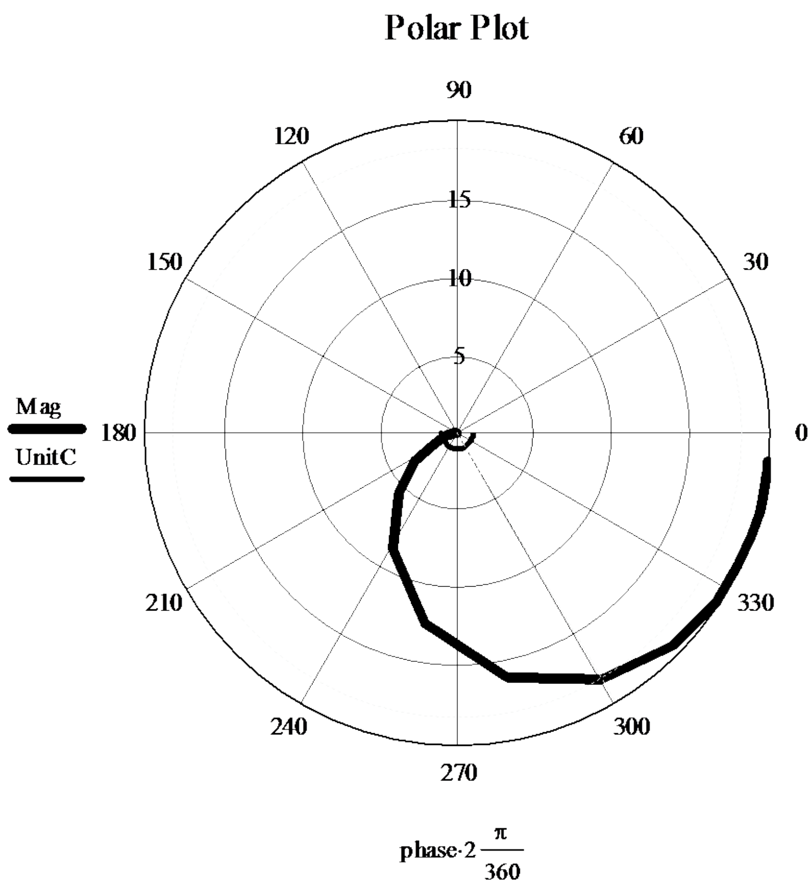


Figure 2 – Polar Plot of a Butterworth Filter as a function of frequency sl

Polar plots are difficult to draw, so Bode plotted the directly measured values of Gain and Phase angle as two traces on a graph. These are the absolute gain of the transfer function and its phase angle in degrees, both vs. frequency.

The final trick with Bode Plots is to recognize that with logarithmic scales, multiplication becomes addition. Gain was converted to decibels (dB). This trick was trivial for anyone who strapped a slide rule to their belt each morning right after breakfast. Bode simplified convolution integrals to plotting straight lines on log paper. He also made some rules for manipulating the lines to give desirable control characteristics of filters and control systems. The logarithm of 1 is zero, so the solution of 1+GH is where the gain is equal to 0dB.

The Bode Plot for the Butterworth filter above is:

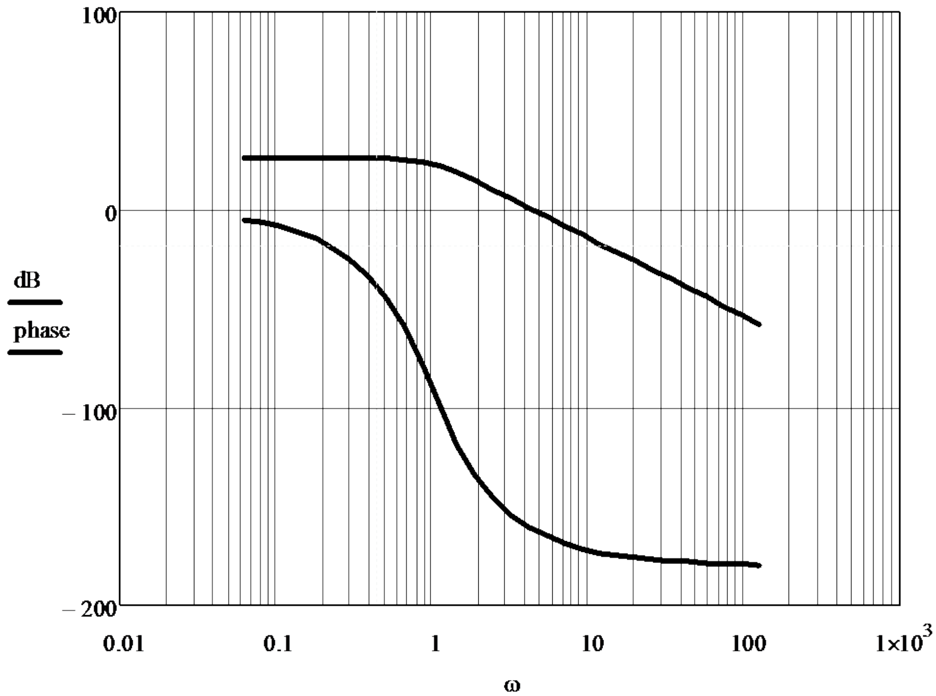


Figure 3 – Bode Plot of a Butterworth Filter as a function of frequency

DRIVE REGULATOR HEURISTICS

Engineers who selected and designed regulators for drive systems used simple heuristics (rules) and regulators that could easily be analyzed by control engineers and easily tuned by competent commissioning engineers or technologists and maintained by plant electricians.

The heuristics were:

1) Use single integrating regulators (Type 1).
2) Inner loops were tuned at least 3 times faster than outer loops.
3) Measure a system lag – set a control lead to cancel it.
4) Set the inner loops fast enough to handle the requirements of the outer loops.
5) Make inner loops fast enough to mask control non-linearities. If the inner loops are fast enough, non-linearities can be ignored completely.
6) Ignore the Bode phase chart where possible.
7) Gain margin and phase margin rules were used by some engineers

<u>Single Integrating Regulators (Type 1) [1]</u>

These are drawn on a Bode plot as straight lines with a slope of -20dB/decade of frequency. The phase is a constant 90 degrees lagging for all frequencies. Each additional integrator increases the slope by -20dB/decade and shifts the phase by an additional 90 degrees lagging.

Single integrating regulators have zero steady state error. That means the regulator is very accurate once it has reached its steady state.

Gain is equal to the regulator response or bandwidth (radians/second).

There is an error in following a ramp, such as an S-Ramp. This error can be compensated with a feed-forward technique called inertia compensation.

These characteristics make the single integrating regulator very easy to tune.

It is interesting to note that each power of $j\omega_n$ (another integration) represents a 90 degree (orthogonal) rotation in the complex plane.

Separation of Cascading Loops by Frequency

Inner feedback control loops can be simplified by the use of Control Block Diagram manipulations (evaluating the closed loop response to eliminate a feedback loop).

It is not mandatory to have inner loops faster than outer loops. The advantage of having inner loops faster than outer loops, is that it permits the inner loop to be modeled with a simple block transfer function with integration and a frequency lag. Because the inner loop is faster than the outer loop, anything the outer loop commands, the inner loop can perform. Control theory indicates the frequency separation should be at least 3 to 10 times faster for the inner loop.

Cancel System Lags with Control Leads

Control transfer function denominators have a number of poles or frequencies where the overall gain is infinite. Solving for the roots of the transfer function denominator determines these frequencies or poles. If a pole in the denominator is known, it can be "cancelled" with a "zero" in the numerator at the same frequency. That is a lead in the numerator. PI regulators can be arranged in a configuration with overall unit-less gain and a lead with units of seconds.

Gain Margin or Phase Margin

Gain margin is the amount (in dB) that the gain would have to be increased before the regulator became unstable. This happens when the phase reaches -180°.

Equivalently the Phase margin is determined at the frequency where the Gain=0dB (crossover frequency), The phase margin is -180º- the phase at the crossover frequency. The phase margin should be at least 45º for stability.

EXAMPLE-SINGLE SPAN TENSION SYSTEM WITH DC DRIVE

Consider a single span tension regulator with requirements for 1 radian/second response. This is controlled with a dc motor and drive, a tachometer and a load cell. A dc motor is selected in keeping with the historical nature of this paper. An ac motor and drive is more complex, but the analysis merges with that for a dc motor once the torque regulator is modeled.

Although important, the motor shunt field current regulator is ignored in this paper. The shunt field current establishes the flux that develops the torque constant Kt as required by the armature current model. The field current regulator is tuned in a similar way to the current rate regulator discussed below. There is no discontinuous case for the field current regulator as there is for the armature current regulator.

The drive system is modeled from the innermost regulator to the outer most regulator. The dc armature regulators are cascaded as:

- Motor armature
- Current Rate Regulator
- Current (Torque) Regulator
- Speed Regulator
- Tension Regulator

The example uses a dc drive circa 1985 [2] to show how the heuristics listed above provide a useful model of the tension control system, simplified to the point that it can be analyzed and tuned by competent personnel in the field. Analog drives use integrators, leads and gains in the time domain. Digital drives prior to 1985 simulated analog regulators directly. Drives developed after about 1985 use state controlled regulators for at least some of the functions.

Tables [3] or computer math programs can be used to perform Laplace and inverse Laplace transforms.

We recognize that various drive vendors implemented different control models [4]. In particular, there are alternatives to the Current Rate Regulator and Speed Rate Regulators discussed below. We observe that the final models for the torque regulator and the speed regulator are common to most drive vendors, and can be extended to ac drives.

DC Motor Armature Model (Locked Rotor Test)

DC motor torque is related to armature current (at a given excitation) by

$$\mathrm{Trq} = \mathrm{Kt} \cdot \mathrm{Ia} \qquad \{6\}$$

where Kt is the motor torque constant with units of N*m/A.

The dc armature transfer function is shown in Figure 4.

The step response of the motor armature current as measured in the locked rotor test gives an armature time constant of Ta=0.006 seconds. The armature parameters may be measured or read on the motor data sheet.

Vrated=600VDC Power=330kW
Iarated=550A
Ra=0.005 ohms
RPM=1150=19.16 Hz

$$\mathrm{Rapu} = \frac{\mathrm{Ra} \cdot \mathrm{Iarated}}{\mathrm{Vrated}} \quad \mathrm{Rapu} = 0.0046 \qquad \{7\}$$

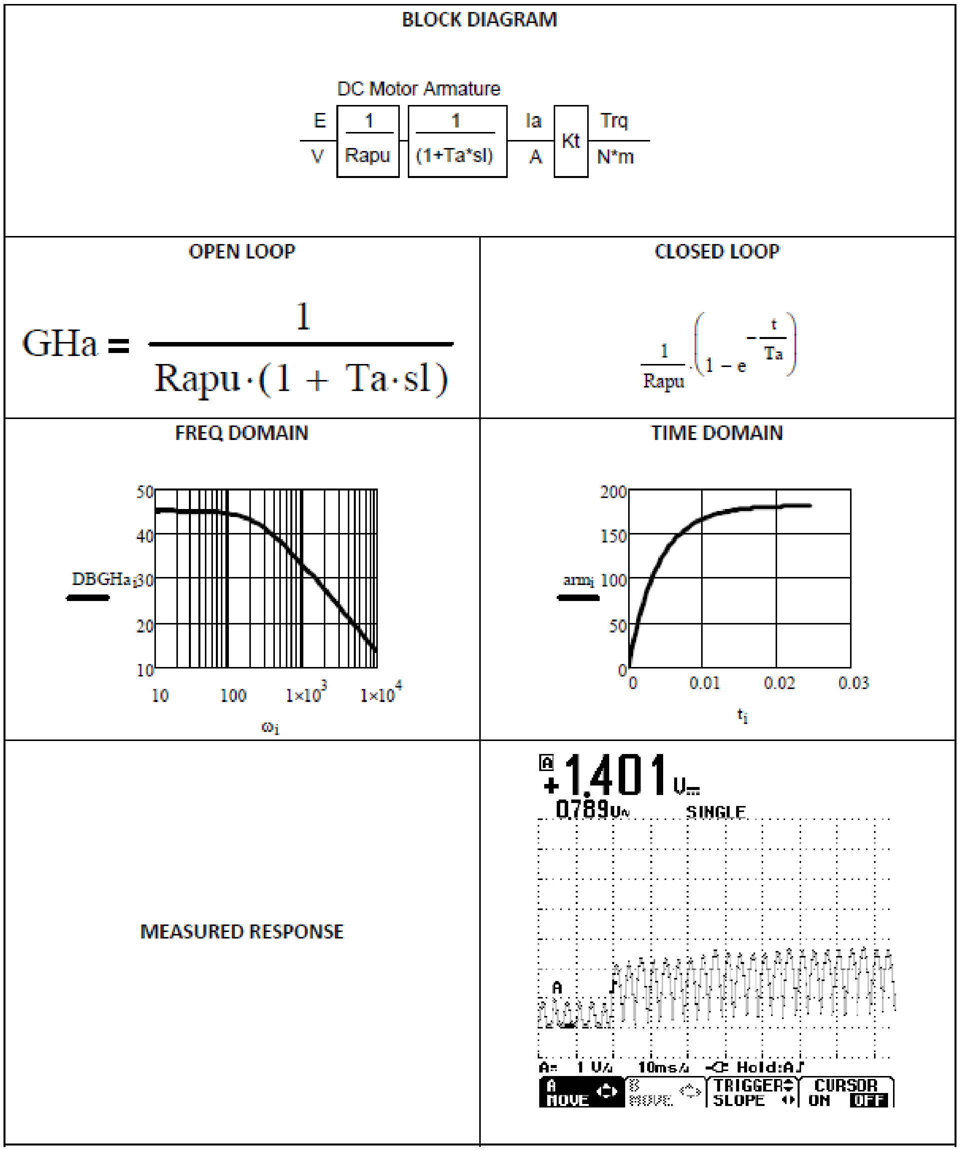


Figure 4 – Armature Firing Time Constant

Current Rate Regulator (CRR)

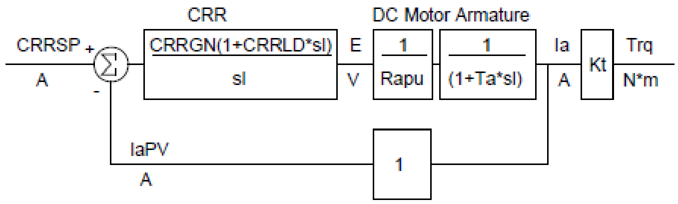
This example uses a fast Current Rate Regulator to overcome the hysteresis of the bridge rectifier in the dc drive. The target response for the Current Rate Regulator is 250 rad/sec. An integrating regulator with a lead is used for the Current Rate Regulator. Using Rule 3), the CRR lead (CRRLD) is set to the measured value of Ta from the Locked Rotor test. The open loop CRR regulator model is

$$GHcrr = \frac{CRRGN\cdot(1 + CRRLD\cdot sl)}{sl}\cdot\frac{1}{Rapu\cdot(1 + Ta\cdot sl)} = \frac{CRRGN}{sl\cdot Rapu} \qquad \{8\}$$

The gain CRRGN is adjusted to give a measured step response of 250 rad/sec. For a 250 rad/sec response, the current rises to its final value in 2 pulses. With a single integrating regulator, Rule 1) indicates the gain is equal to the regulator response and should be

$$\mathrm{CRRGN} = \mathrm{Wcrr} \cdot \mathrm{Rapu} \quad \mathrm{CRRGN} = 1.146\frac{1}{s} \tag{9}$$

BLOCK DIAGRAM



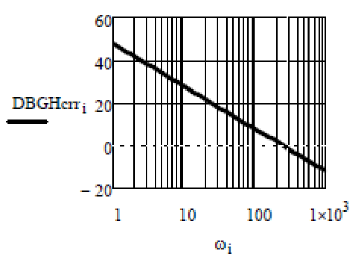
OPEN LOOP

$$\mathrm{GHcrr} = \frac{\mathrm{CRRGN}(1 + \mathrm{CRRLD}\,\mathrm{sl})}{\mathrm{sl}} \cdot \frac{1}{\mathrm{Rapu}\cdot(1 + \mathrm{Ta}\cdot\mathrm{sl})}$$

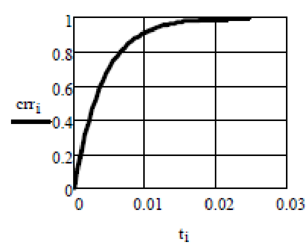
CLOSED LOOP

$$\frac{\mathrm{CRRGN}}{\mathrm{CRRGN} + \mathrm{Rapu}\cdot\mathrm{sl}} \qquad 1 - e^{-\frac{\mathrm{CRRGN}}{\mathrm{Rapu}}\cdot t}$$

FREQ DOMAIN



TIME DOMAIN



MEASURED RESPONSE

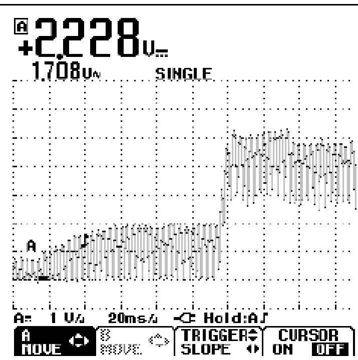


Figure 5 – Current Rate Regulator

The trace above shows continuous current. When current is lower, the CRR must automatically increase gains for discontinuous current to maintain a CRR response of 250 rad/sec for continuous or discontinuous operation.

The closed loop transfer function for the CRR and its time domain step response is shown in Figure 5.

Current Regulator (CR)

This example uses an integrating Current Regulator without leads or lags. A target of 20 rad/sec is desired for the CR. The open loop transfer function for the CR is:

$$\frac{\mathrm{CRGN}}{\mathrm{sl}} \cdot \frac{\mathrm{CRRGN}}{(\mathrm{Rapu} \cdot \mathrm{sl} + \mathrm{CRRGN})} = \frac{\mathrm{CRGN}}{\mathrm{sl}} \qquad \{10\}$$

Rule 1) indicates the CR gain should be set to the desired response CRGN=20 rad/sec.

The closed loop CR transfer function and time domain step response are given in Figure 6.

Note that in order to protect the motor, several non-linear limits are added to the regulator. These are current limits which limit motor current and torque typically at 2 pu. In addition, the rate of change of armature current is limited typically at +/- 20pu/sec.

We observe that an ac drive also has a torque regulator. Please note that in a dc drive with constant flux, armature current and torque are closely related. The torque regulator in an ac motor may be modeled with the same transfer function as the dc drives current regulator. The response of the ac drive torque regulator may be faster than that for a dc drive at perhaps 300 rad/sec.

From this point on we will refer to the current regulator as the torque regulator. From this point on we will refer to either an ac or dc drive as the drive.

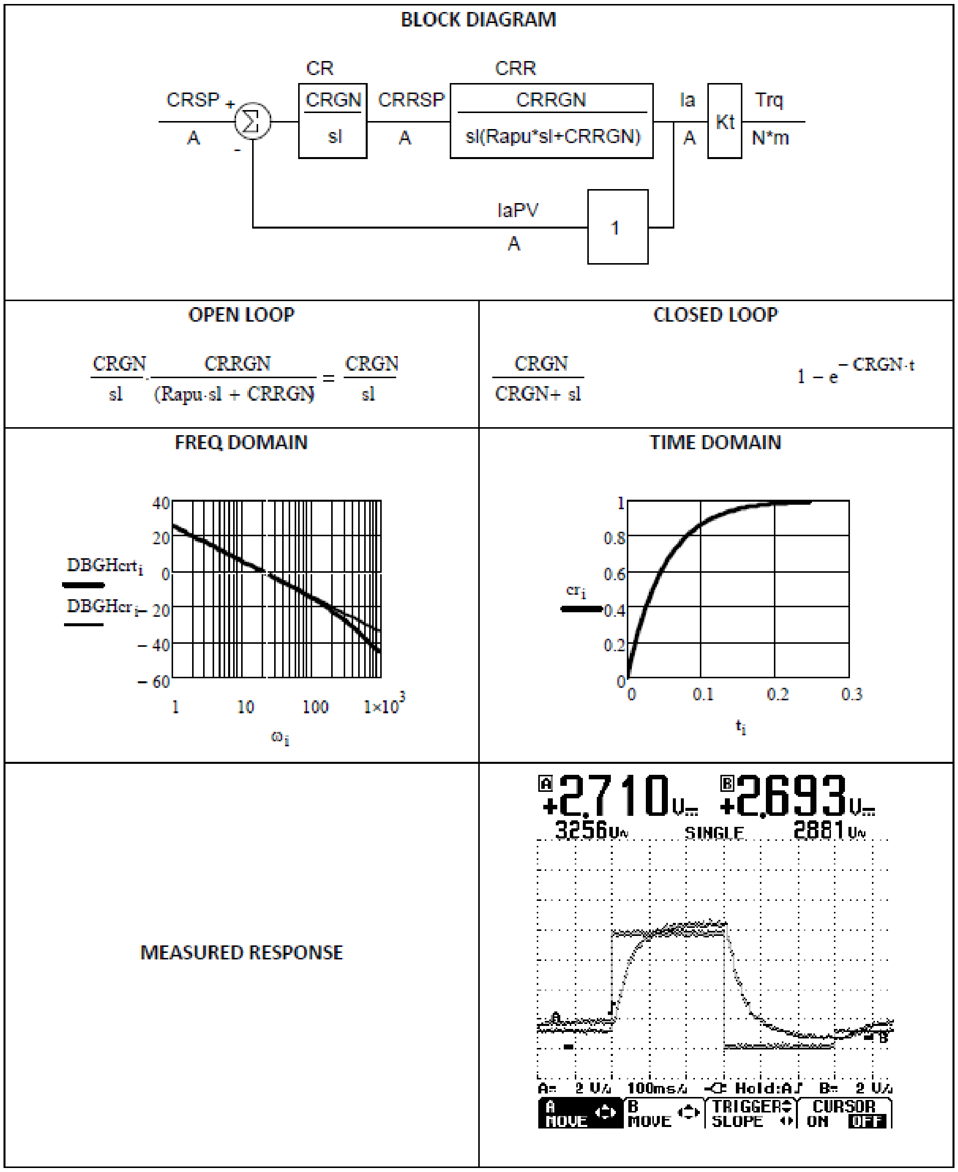


Figure 6 – Current Regulator

Speed Regulator

The torque regulator involves transfer functions of the motor and drive only. This is the inner regulator and a simplified model is used. Heuristics listed above were used to guide in the simplification of the torque regulator.

The analysis of the speed regulator adds the inertia (J) of the driven roller to the system. The inertia is reflected to the motor side of any speed reducer in the system. For simplicity, inertia J is often normalized with units of seconds to reach design speed at the motor's rated torque and its torque constant Kt.

The model of the roller driven by torque supplied by the drive is

$$\frac{1}{J \cdot sl} \qquad \{11\}$$

Speed Rate Regulator (SRR)

The speed rate regulator uses speed feedback from a tachometer on the motor and compensates for the inertia of the roller and drive train. The open loop transfer function of the SRR is

$$SRRGN \cdot \frac{CRGN}{CRGN + sl} \cdot \frac{1}{J \cdot sl} = \frac{SRRGN}{J \cdot sl} \qquad \{12\}$$

If the desired response of the SRR is much lower than the torque regulator, we may ignore the torque regulator using Rule 4). The SRR open loop gain then simplifies as shown in {12}.

The gain SRRGN is adjusted to give a desired step response of 0.5 rad/sec. Assume a normalized inertia of 100 seconds. With a single integrating regulator, Rule 1) indicates the open loop gain is equal to the regulator response and should be

$$SRRGN = 0.5\frac{rad}{sec} \cdot J \quad SRRGN = 50 \qquad \{13\}$$

The closed loop transfer function and time domain step response for the speed rate regulator is shown in Figure 7.

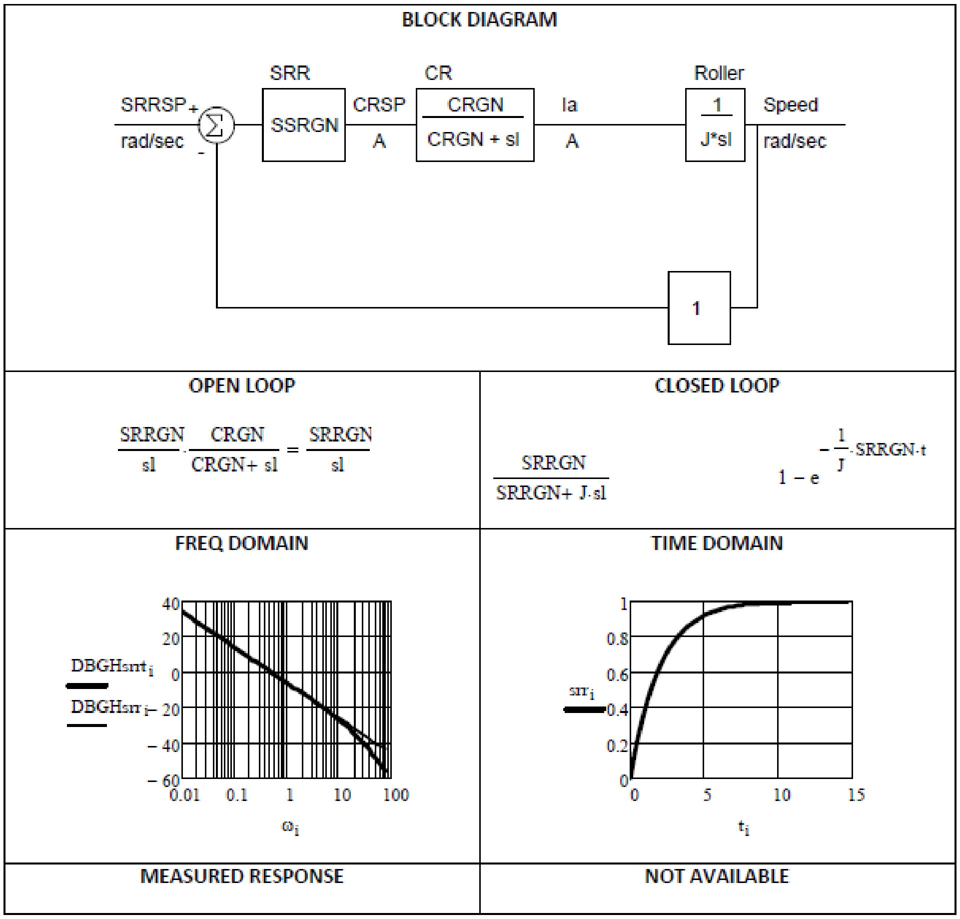


Figure 7 – Speed Rate Regulator

Speed Regulator (SR)

The speed regulator uses speed feedback from a tachometer on the motor. It uses a regulator with gain and a lead. The SRR isolates the SR from the motor inertia. The open loop transfer function of the SR is

$$\frac{SRGN \cdot (1 + SRLD \cdot sl)}{sl} \cdot \frac{SRRGN}{SRRGN + J \cdot sl} = \frac{SRGN}{sl} \qquad \{14\}$$

Using rule 3), set the speed regulator lead SRLD equal to the measured speed rate regulator time constant J/SRRGN = 2 sec. The open loop transfer function of the speed regulator then simplifies to a single integrating system as shown in {14}.

Using Rule 1) for a single integrating regulator, the response of the regulator is equal to the gain of the speed regulator (SRGN).

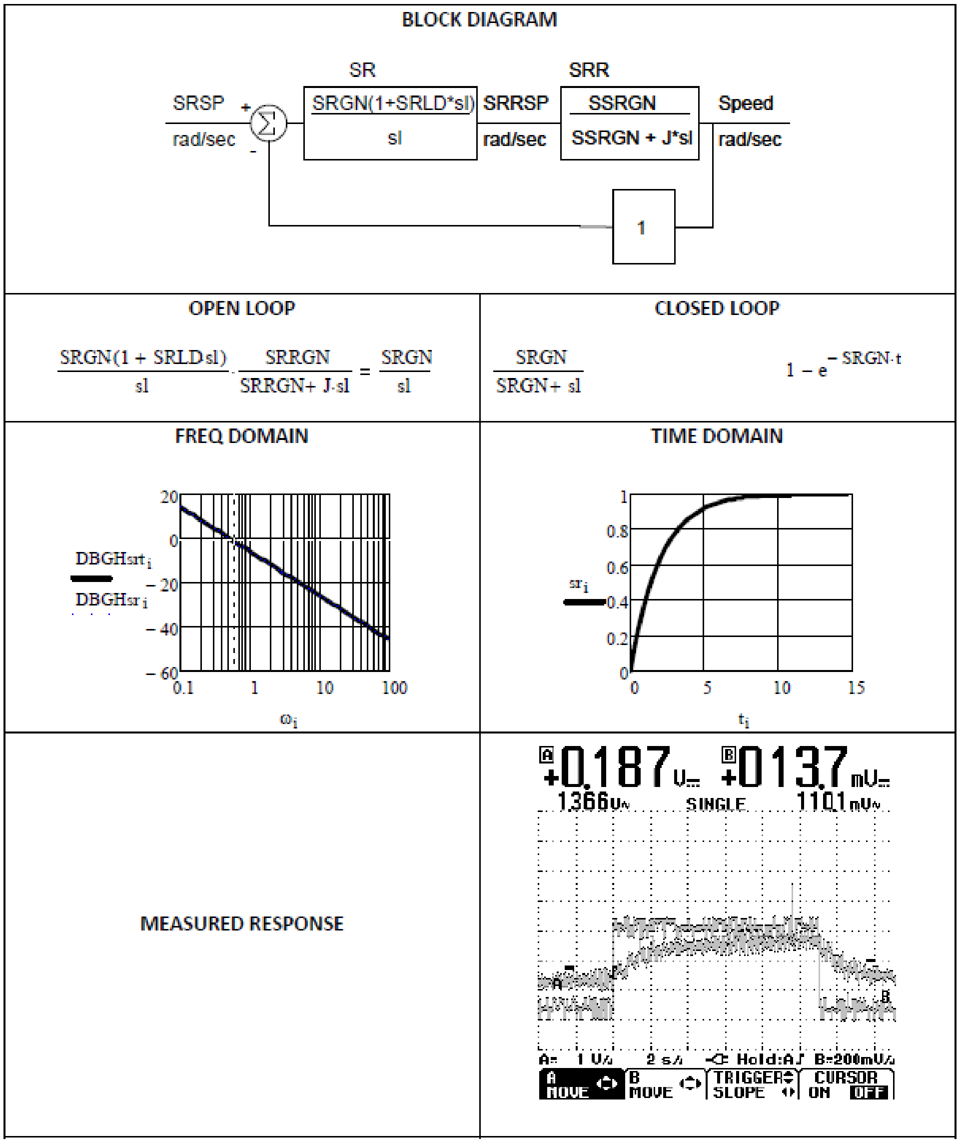


Figure 8 – Speed Regulator

Tension Regulator (TR)

Shin [5] provides a model of a single span tension regulator with load cells and an ISA-PID controller into the current regulator for a dc drive.

Drive systems engineers use the ISA-PID regulator which is given as

$$G_c = K_p + \frac{K_i}{sl} + K_d \cdot sl \qquad \{15\}$$

A change in gain keeps the leads and lags unchanged.

The model of a single span tension regulator is shown in Figure 9. 3rd order Laplace equations cannot be found in transformation tables. We often use a Heavyside expansion to find the inverse Laplace transform (time domain solution). To do this, all the roots of the characteristic equation are found and substituted into the equation as shown in the Closed Loop part of Figure 9. The variable r_n represents each of the complex roots of the characteristic equation.

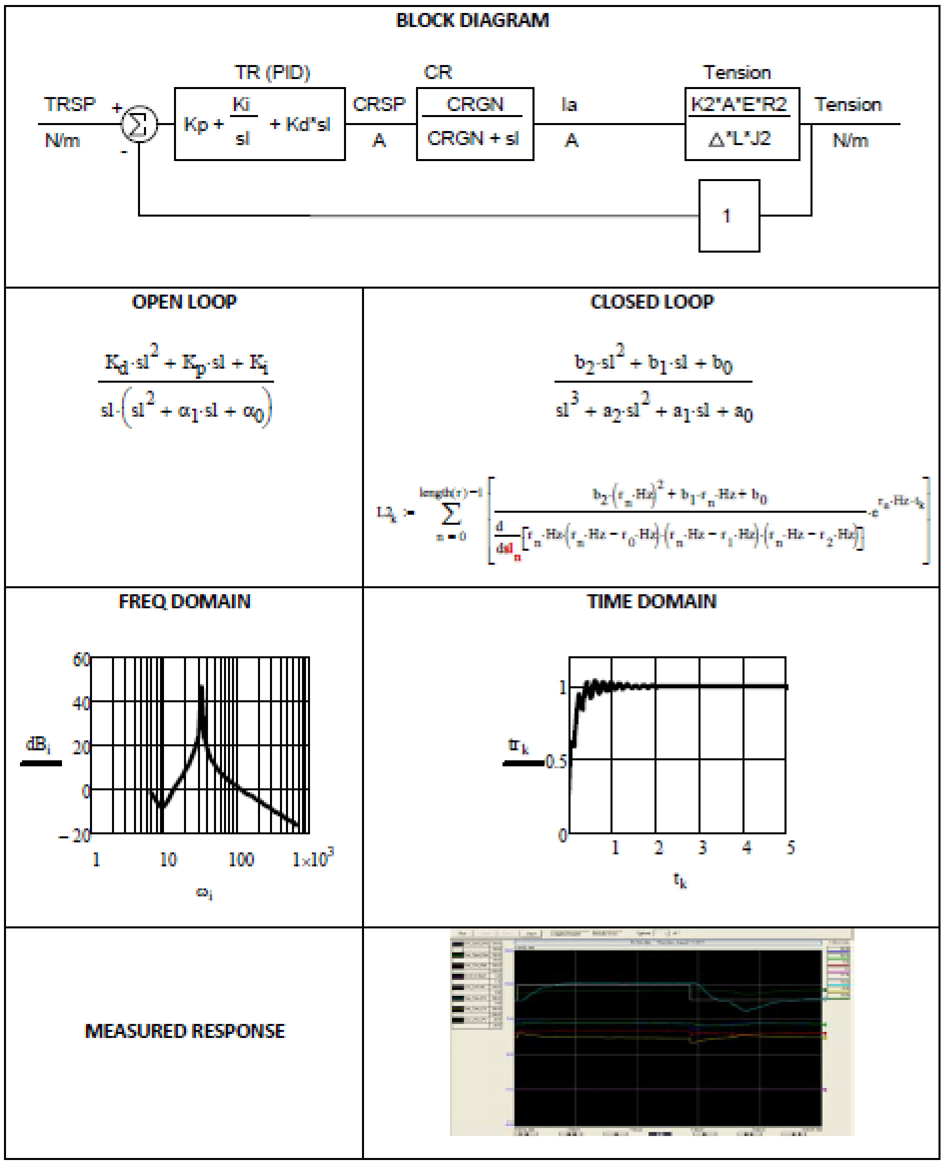


Figure 9 – Tension Regulator

Variables used in Figure 9 are defined as

$K_p = 4 \times 10^{-4}$ - Proportional Gain of ISA-PID controller

$K_i = 0.02\frac{1}{s}$ - Integral Gain of ISA-PID controller

$K_d = 2.5 \times 10^{-5} s$ - Integral Gain of ISA-PID controller

$K_2 = 31\frac{A \cdot s^2}{m \cdot kg} \cdot \frac{N \cdot m}{amp}$ - Motor torque constant

$A = 6.71 \times 10^{-4} m^2$ - cross sectional area of the web

$E = 3.84 \times 10^3 \cdot MPa$ - Young's modulus (paper)

$R_2 = 0.076m$ - Roller radius

$v_{20} = 0.254\frac{m}{s}$ - web velocity at roller 2

$$\Delta = sl^2 + \left(\frac{v_{20}}{L} + \frac{B_{f2}}{J_2}\right) \cdot sl + \frac{v_{20} \cdot B_{f2}}{L \cdot J_2} + \frac{A \cdot E \cdot R_2^{\,2}}{L \cdot J_2}$$

$L = 1.5m$ - length of web

$J_2 = 10m^2 \cdot kg$ - moment of inertia of the roller

$B_{f2} = 1 \cdot N \cdot m \cdot s$ - Rotary Friction constant of the roller bearing

$$\alpha_0 = \frac{v_{20} \cdot B_{f2}}{L \cdot J_2} + \frac{A \cdot E \cdot R_2^{\,2}}{L \cdot J_2} \qquad \alpha_1 = \frac{v_{20}}{L} + \frac{B_{f2}}{J_2}$$

$$\beta_0 = K_2 \cdot \frac{A \cdot E \cdot R_2}{L \cdot J_2}$$

$$a_0 = \beta_0 \cdot K_i \qquad b_0 = \beta_0 \cdot K_i$$

$$a_1 = \alpha_0 + \beta_0 \cdot K_p \qquad b_1 = \beta_0 \cdot K_p$$

$$a_2 = \alpha_1 + \beta_0 \cdot K_d \qquad b_2 = \beta_0 \cdot K_d$$

SPECIAL CASES

Once we know the expected response for each of the regulators, we can understand problems not covered by the model when they present themselves. Problems may include backlash and resonances.

Non-linear electronic devices (vacuum tubes, Thyristors, GTO's) with hysteresis have been used since the beginning. In fact, the devices in use today are more non-linear than historical devices.

Non-linear events (torque limit, speed limit, slip, web break, gear backlash) require regulator mode changes.

Lead/Lags are used to compensate for overshoot when it appears.

Bad rules propagated as quickly as the good rules using technology of the day – conferences, phone calls, telex and photocopiers. Ideas that did not work were often left "clinging on" to the control system and were copied to the next job.

PHASE SHIFT

Each integrator in a control loop shifts the phase by 90 degrees lagging. Once the phase shift reaches 180 degrees, the negative feedback required for a control regulator is lost. The phase shift makes the feedback positive, resulting in instability. By using single integrating regulators and separating cascading loops by frequency, we can ensure that the phase shift remains less than 135 degrees lagging and the regulators can be tuned to be stable.

By following the heuristics listed above, we do not even have to consider the phase shift (Rule 6).

REGULATOR MODE CHANGES

At certain times or for different tasks we need different regulators. Today the speed regulator is used for threading. Torque control may be required for emergency stopping or following a web break. We need a defined method of switching between these regulators. The transition should be bumpless. Specifically I anticipate a future state-space regulator perfectly configured for excellent tension control. How does one thread this section before tension can be established? How does it respond to a web break. How does a spindle drive perform a smooth cutover on a turret winder?

TECHNOLOGY CHANGES

Over the years classical rules applied even when technology changed. The progression was:

- DC M-G sets with vacuum tube through the field regulators

- DC motors with static armature regulators
- Analog computers (operation amplifiers)
- Digital computers (simulate analog computers)
- Digital state control regulators – now in place for torque and speed – not for tension

These state control regulators rely on pure math. The drive user manuals do not describe the operation, tuneup or regulator troubleshooting methods. The drives include auto-tune. We must ask what does auto-tune do and what is the resulting response? How well does it tune the drive? Drive vendors hide the strategy as "too complicated for us" or as proprietary.

CONCLUSIONS

We need to maintain a control design strategy for drives in web handling. The drives industry started with a strategy 60 years ago. We may be losing sight of that strategy today as technology advances. Auto-tuning has taken the awareness of the strategy away from control engineers and startup personnel. New engineers may not even know there was a strategy as they design their modern drive systems. Commissioning personnel are not able to analysis the system. They require a simple strategy for tuning drives and commissioning web handling lines.

Modern control methods are good and may be much better than present controls. We must ensure they are implemented in a way that results in control that is better than equivalent classical control methods. Metrics such as a step response or bandwidth that were easy to measure were useful in the past.

I would prefer to use metrics before answering ongoing questions such as comparing load cells with dancers, comparing ac and dc drives, or whether auto-tuning is providing adequate control for web handling.

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